The Effect of Quadriceps Weakness in Older Adults on Lower Extremity Muscle Function During Gait

Undergraduate Research Thesis

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Abstract

Osteoarthritis is a painful condition that generally causes patients to experience weak quadriceps, abnormal gait kinematics, and difficulty completing daily movements. The quadriceps muscles are a vital muscle group in the lower extremities that brake the body's center of mass and provide vertical support during activities such as walking. Previous research investigated simulated muscle compensations for quadriceps weakness in a healthy young adult population; however, no research has analyzed muscle compensations for weak quadriceps in older subjects during gait. The project determined estimated muscle compensations for simulated quadriceps weakness, based on changes in muscle forces and contributions to support and progression, in older healthy adults. Quadriceps weakness was simulated using the dynamic computer simulation software OpenSim, on 10 healthy older adults. The muscles that increased their peak force the most in older adults during the simulated quadriceps weakness were the medial gastrocnemius and gluteus maximus. The medial gastrocnemius and gluteus maximus increased contribution to both support and progression while the gluteus medius and soleus both increased contributions to progression. The gluteus maximus increased its peak force and contributions to support and progression in both the younger and older adults with simulated quadriceps weakness. The soleus did not compensate for quadriceps weakness in older adults as much as in young adults. The medial gastrocnemius was found to be more of a primary compensator for older adults but not young adults.

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1. Introduction

1.1 Osteoarthritis

Arthritis is a degenerative joint disease that affects the knees, hips, and feet. About 49.9 million American adults (22.2% of the adult population) were diagnosed with arthritis between 2007 and 2009 [1]. By 2030 that number is estimated to increase to 67 million (25% of adult population) adults [2]. These numbers make arthritis the leading cause of disability in the United States, along with being a large clinical burden [2]. Osteoarthritis (OA), the most common form of arthritis, occurs when the cartilage at the ends of bones wear down over time [3]. Twenty-seven million adults (10% of the US adult population) were diagnosed with OA in 2005, and, in 2009, OA was the fourth most common cause of hospitalization [1].

1.1.1 Knee Osteoarthritis

In the United States, knee OA is a leading cause of OA-related impairments. Considering the older adult population age 60 or greater, nearly 12% have symptomatic knee osteoarthritis (KOA) [4]. It has been shown that adults with KOA have altered gait kinematics [5, 6], including decreased knee range of motion and angular velocity, decreased stride length, and slower walking speeds compared to a young population [7]. Adults with knee OA often experience discomfort and pain when completing daily tasks such as walking, rising from a chair, and climbing stairs [8, 9].

1.2 Muscle Functions

Muscle strength is vital to perform daily activities and is strongly associated with a higher quality of life [10]. During the gait cycle, the muscles in the lower extremities work together to move the body’s center of mass (COM) by contributing to upper body support and forward progression (Figure 1) [11]. The major contributors to support and progression during the gait cycle include the gluteus maximus, gluteus medius, soleus, quadriceps, tibialis anterior, and gastrocnemius [12].

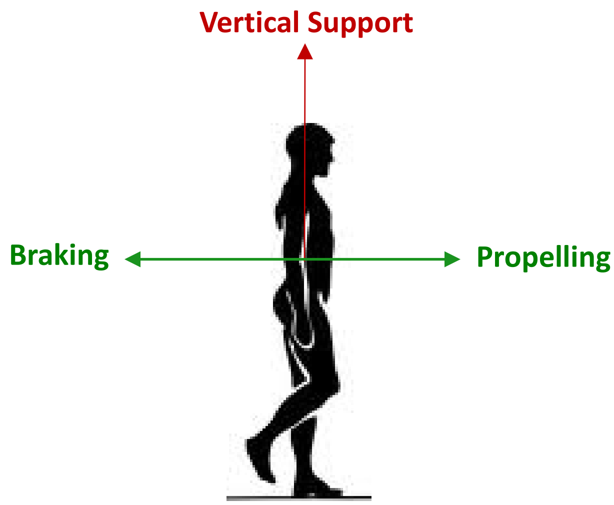

Figure 1: Direction of acceleration: progression (braking and propelling) and vertical support

The gluteus maximus provides vertical support and braking during early stance (Figure 2), while the gluteus medius propels the center of mass during late stance [13]. The soleus brakes the COM during mid-stance and during late stance propels the COM and provides vertical support [3]. The gastrocnemius propels the center of mass and provides vertical support during late stance [13].

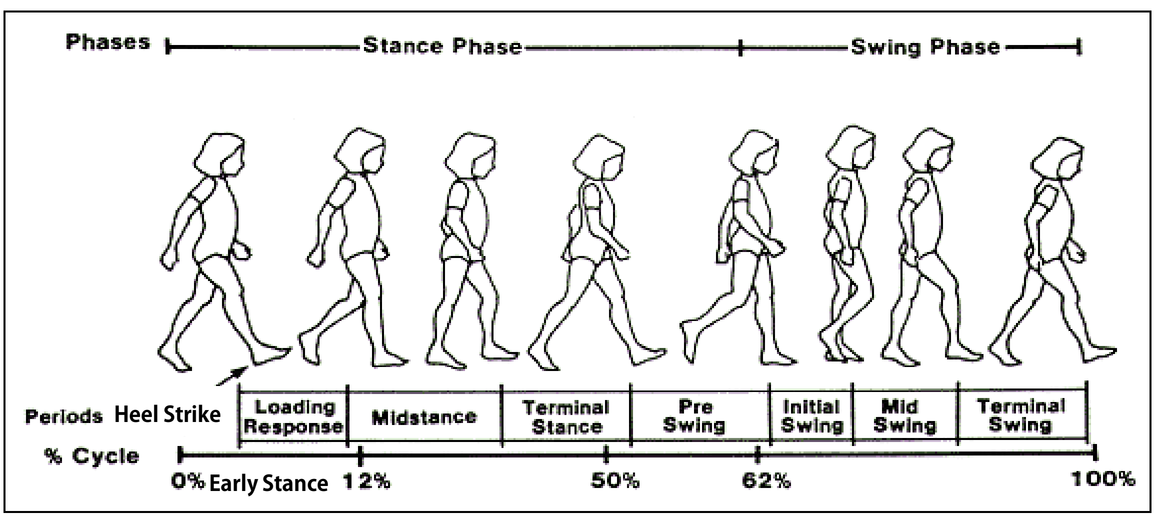

Figure 2: Schematic of the gait cycle

1.3 Quadriceps Function and Weakness in KOA

The quadriceps, a group of four muscles (vastus intermedius, vastus medialis, vastus lateralis, and the rectus femoris (Figure 3)), aide in both vertical support and progression. During early stance the quadriceps help brake the body's COM and provide vertical support. The use of the quadriceps is vital not only during gait but also in completion of everyday activities. Due to quadriceps weakness, which is often associated with knee OA, the quadriceps can no longer produce the same peak force as before during activities such as walking or climbing stairs. One source of quadriceps weakness is atrophy. Atrophy is the wasting away or shrinking of a muscle due to inactivity or degeneration of cells [14]. Quadriceps weakness is often associated with a decrease in speed, abnormal gait, joint pain and damage [15]. Consequences of quadriceps weakness can include increased fall risk [16] and decreased performance during daily activities [17, 18, 19].

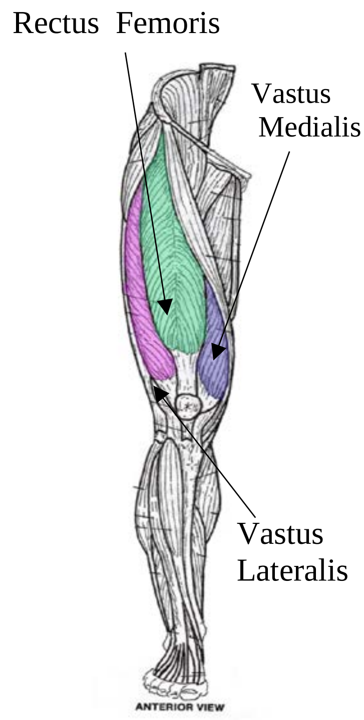

Figure 3: Quadriceps muscle locations (vastus intermedius not shown)

1.4 Previous Research

Previous research has been performed in young adults (ages 19-24) to analyze changes in muscle forces and contributions to support and progression in response to simulated quadriceps weakness [12]. The study showed regardless of the type of quadriceps weakening, atrophy or activation failure, muscle forces and contributions to support and progression changed to compensate for the weak quadriceps in order to maintain normal gait. The study found that the gluteus maximus and soleus were the only muscles to increase their average peak forces and average contributions to support and progression in response to weakened quadriceps [12]. The gluteus maximus was found to be the primary compensator, regardless of the type of weakness [12].

1.5 Gaps in Knowledge

Although the main muscles that compensate for simulated weakened quadriceps are known in a young adult population, no research has investigated simulated quadriceps weakness in older adults. Studies have shown older adults exhibit decreased knee extension, a shorter stride length, a more flexed hip and increased plantar flexion at toe off compared to younger adults during gait [20]. These kinematic differences may lead to differences in muscle peak forces and contribution to support and progression between healthy older and young adults. Along with older adults having osteoarthritis, the differences could affect which muscles are used to compensate for the weakened quadriceps between older and younger adults.

1.6 Purpose of Thesis

The purpose of this study was to estimate the changes in muscle forces and contributions to support and progression required to maintain the gait of healthy older adults in response to simulated quadriceps weakness. Secondarily, this study examined differences in how older and young adults compensated for quadriceps weakness due to atrophy during gait.

1.7 Significance of Research

It is still widely unknown how age-related differences such as kinematics, magnitude of muscle force, and muscle function are related to each other and how these differences can affect walking ability. This project could lead to a better understanding of how muscles are controlled and utilized to maintain gait in an older adult population. Gaining a better understanding of muscle function during gait through this study may help clarify essential factors for older adults to maintain their ability to perform physical activities.

1.8 Organization of Thesis

This thesis consists of 5 chapters. Chapter 2 describes the detailed procedure on how quadriceps weakness was simulated along with the data processing steps. Chapter 3 reports the results and analysis, which are discussed further in Chapter 4. Chapter 5 provides a summary of the thesis and includes a discussion on future directions and limitations of the project.

2. METHODS

2.1 Introduction

This project is an extension of graduate student Sarah Schloemer's dissertation work examining changes in muscle function and motor control during gait due to aging and KOA. Data was collected at the University of Wisconsin-Madison. All subjects were healthy and passed an initial phone screening that included current or history of orthopedic diagnosis, joint pain, or known cardiac, neurologic, gait or balance impairments [20]. The motion capture data of one trial was used and processed to analyze muscle forces and contributions to support and progression during the gait cycle. Initial scaling of the subjects and gait simulations of the older adults at full strength were conducted by graduate student, Sarah Schloemer.

2.2 Experimental Data

Ten healthy older adults (3 Males and 7 Females 73.9+-5.3 years) participated in this study. Motion data was tracked using 23 markers on anatomical landmarks, along with 19 tracking markers to reduce the effects of soft tissue artifact [21]. Subjects walked five times at a self-selected speed, and one representative trial was chosen for each subject for further analysis. Using an 8 camera passive motion system (Motion Analysis Corporation, Santa Rosa, CA) the trajectories of the markers were collected and processed using motion capture software (EVaRT v5.0). Ground force reactions during a full gait cycle for both legs were recorded using 3 imbedded force plates (model BP400600, AMTI, Watertown, MA). To measure muscle activation patterns, surface electromyography (EMG) was collected using pre-amplified single differential surface electrodes (DE-2.1, DelSys, Inc, Boston, MA) placed on the rectus femoris, vastus lateralis, biceps femoris, tibialis anterior, medial hamstrings, gastrocnemius, and soleus [20]. All data was collected by Amy Silder at the University of Wisconsin-Madison and used for further analysis at the Nueromuscular Biomechanics Laboratory at The Ohio State University.

2.3 Simulations and Modeling

One full gait cycle at the subject's self-selected speed was simulated using OpenSim software version 3.1 (Figure 4). The dynamic musculoskeletal Arnold 2010 model [22] was used to scale the dimensions of each body segment to match the anthropology of the individual subjects based off of relative distances between pairs of anatomical markers [22,23]. To reproduce the raw marker data gathered from the motion capture system, an inverse kinetics problem was solved to find the joint angle trajectories. To reduce dynamic inconsistency of the body segment acceleration and ground reaction forces, a residual reduction algorithm (RRA) altered mass properties and joint kinematics [23]. Static Optimization (SO) with an objective function that minimized the sum of the squared muscle activation was used to estimate muscle activations and forces [23]. The activations from SO were compared to experimental EMG to confirm consistency between the simulated and experimental muscle activation patterns [12]. An instantaneous potential for acceleration (IPA) was calculated using the kinematics from RRA to determine individual potentials for the muscles to contribute to support and progression. An Induced Acceleration Analysis (IAA) was then completed by multiplying the estimated muscle forces from SO by the IPA of each muscle to determine the individual muscle contributions to the support and progression of each subject [23].

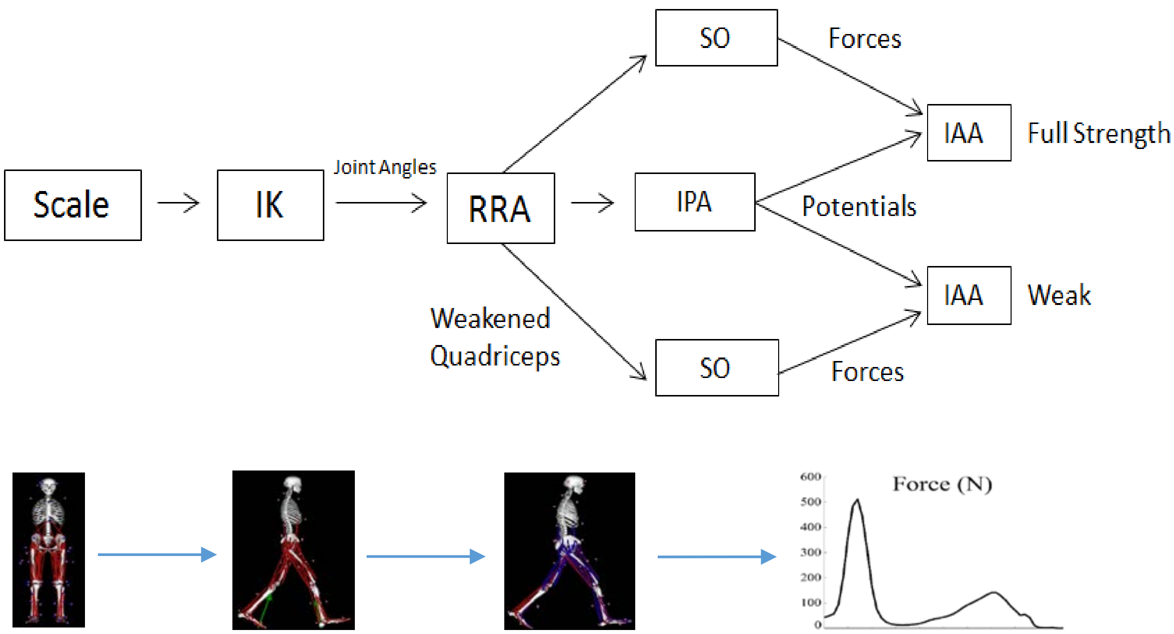

Figure 4: Steps used in OpenSim to analyze motion data and calculate the contributions to support and progression with weakened quadriceps

2.4 Weakened Quadriceps Simulations

To simulate atrophy, the quadriceps were weakened from the original model by reducing the peak isometric force of the four quadriceps muscles of each leg by 60% of their original values (Table1) .

Table1: Original quadriceps strength and strength of quadriceps after weakening

Muscle	Original Strength (N)	Atrophied Strength(N)
Rectus Femoris	1169	467.6
Vasti Intermedius	1365	546
Vasti Medialis	1294	517.6

Vasti Lateralis	1871	748.6

Static Optimization was rerun for each subject using the model with weakened quadriceps (Figure 4) to estimate muscle forces and activations. IAA, as described before, was implemented to find the individual muscle contributions to the support and progression of the body's COM.

2.5 Data Analysis

Custom Matlab code was written to find the average peak forces and contributions to support and progression for each muscle in the weakened and full strength models. Peak muscle forces and contributions to support and progression of the weakened models were compared to the data from the full strength models. The differences between peak muscle forces of the two models were calculated as the peak individual muscle force from the full strength subjects subtracted from the peak individual muscle force from weakened model. This resulted in the magnitude of change between the muscles' peak forces and contributions to support and progression. For each subject, the percent change in the individual muscle's peak force was calculated using Equation 1, where "i " represents the individual muscle being calculated.

$$\%\, Change\ of\ muscle\ force = \frac{Peak\ Muscle\ Force\ (i)_{Weak} - Peak\ MuscleForce\ (i)_{Full\ Strength}}{Peak\ Muscle\ Force\ (i)_{Full\ Strength}}\ x\ 100 \qquad \text{(Equation 1)}$$

Similar equations were used to calculate the percent change in peak muscle contributions to progression and support between the models. Major muscles compensators for older adults with simulated quadriceps weakness were determined by analyzing the absolute difference between the full strength and weakened models and percent change in peak forces and contributions to support and progression. The percent changes in peak forces and contributions to support and progression from the older were then compared to percent changes for young adults [12] were then compared. A general linear model repeated measures analyses of variance (ANOVA) was performed to determine if changes in peak muscle force and contributions to support and progression between weakened and full strength models were significant. This same test also determined if changes in between age groups were significant.

3. RESULTS

In all subjects, the simulation was able to track normal older adult gait successfully. Most muscles changed their force output and contributions to support and progression in response to quadriceps weakness. Due to quadriceps weakness, there was a significant difference in the percent change in force ($p<0.001$) and progression ($p<0.001$) between the muscles. There was no significant difference in the percent change in support between muscles. The muscles in the weakened models produced significantly different amounts of force and contributions to progression and support (Table2) compared to the full strength models (TableA2).

Table2: Peak muscle forces and contributions to support and progression in weakened quadriceps model for older adults

Muscle	Average Peak Force (N)	Average Peak Support(m/s^2)	Average Peak Progression (m/s^2)
Biceps Femoris (lh)	251.327738	0.3811	0.1534
Biceps Femoris (sh)	247.5746	0.1315	0.1918
Gastrocnemius (Lateral)	142.70	0.3284	0.2273
Gastrocnemius (Medial)	976.8721	1.3221	0.6687
Gluteus Maximus	506.1132	2.4154	-0.1157
Gluteus Medius	976.8721	2.1706	0.0445
Rectus Femoris	255.1066	0.479	-0.3664
Soleus	2.05E+03	8.4199	1.2483
Tibialis Anterior	256.535	2.3487	-0.6711

Vastus Intermedius	222.2198	1.074	-0.3259
Vastus Medialis	383.6148	1.9157	-0.5809
Vastus Lateralis	143.5662	0.6886	-0.2088
Standard Deviation	38.1901	0.1624	0.0536

3.1 Muscle forces in weakened older adults

The major muscles that increased their peak force in response to weakened quadriceps were the medial gastrocnemius and gluteus maximus (Table 3). The medial gastrocnemius displayed the largest average percent change increase in force ($p<0.001$). Figures 5 and 6, illustrate the average forces of the medial gastrocnemius and gluteus maximus in the weakened and full strength models across the gait cycle.

Table 3: Average changes in individual peak muscle force between healthy older adults and older adults with quadriceps weakening

Muscles	Mean Difference(N)	% Change
Biceps Femoris (lh)	-22.44	-8.9%
Biceps Femoris (sh)	-24.69	-10.0%
Gastrocnemius (Lateral)	-37.24	-26.1%
Gastrocnemius (Medial)	**399.70**	**40.9%**
Gluteus Maximus	**45.58**	**9.0%**
Gluteus Medius	-9.46	-1.0%
Rectus Femoris	-139.33	-54.6%
Soleus	-60.53	-2.9%
Tibialis Anterior	-39.43	-15.4%
Vastus Intermedius	-57.95	-26.1%
Vastus Medialis	-64.12	-16.7%
Vastus Lateralis	-57.12	-39.8%

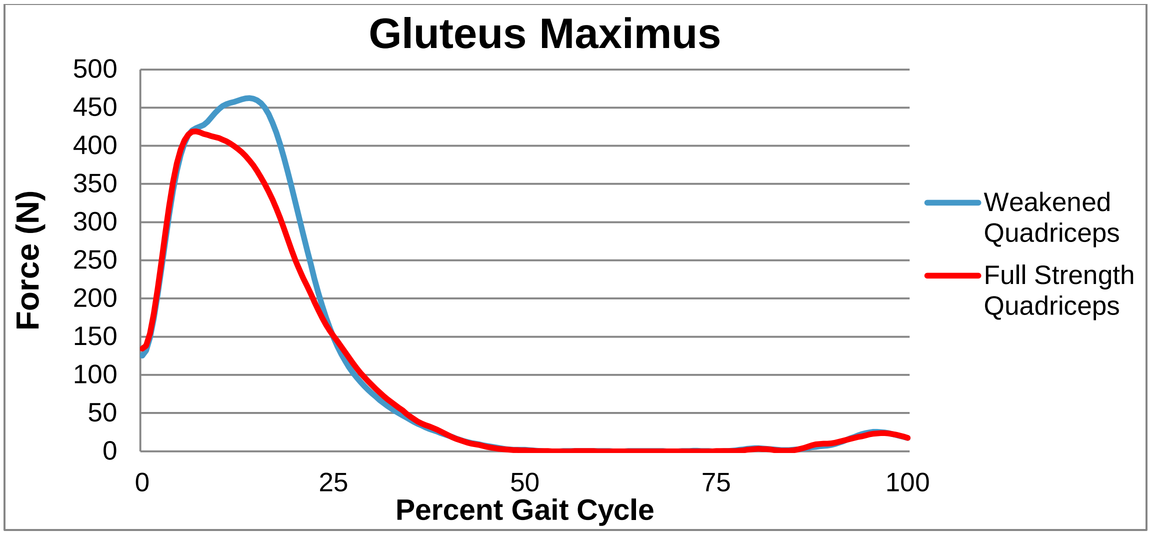

Figure 5: Force generated by the gluteus maximus muscle in the weakened and full strength model.

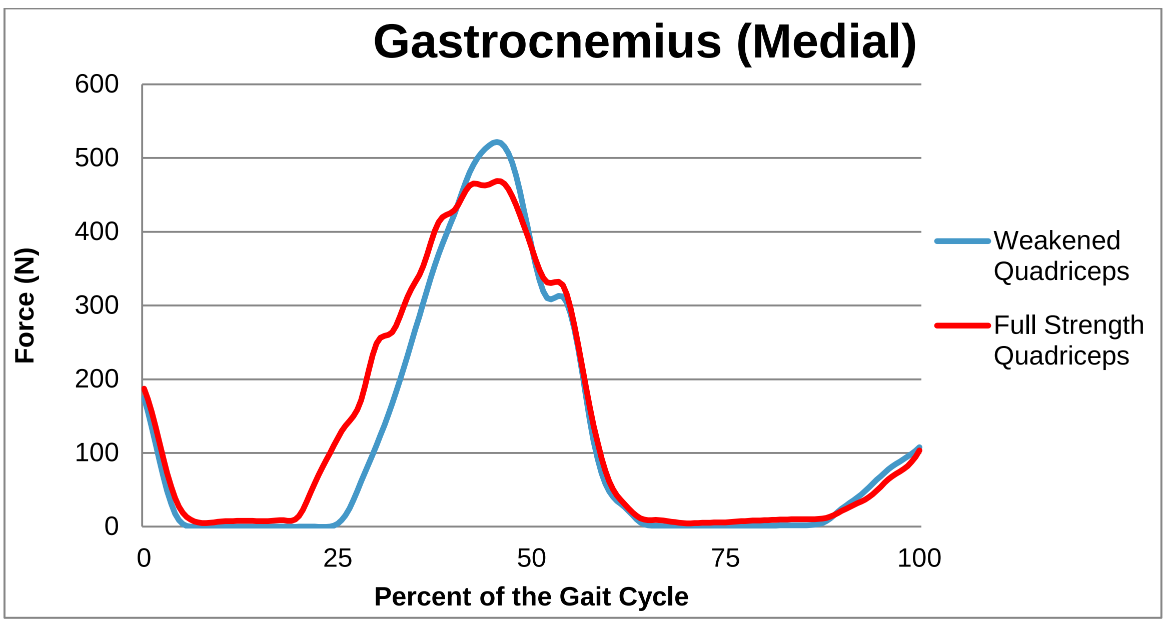

Figure 6: Force generated by the medial gastrocnemius muscle in the weakened and full strength model.

3.2 Contributions to vertical support in weakened older adults

The major muscles that increased their contributions to vertical support in response to quadriceps weakness were the medial gastrocnemius and gluteus maximus (Table4). As seen in force output, the medial gastrocnemius produced the largest percent increase in vertical acceleration; however, no significance between muscles was found. Figures 7 and 8 illustrate the average contributions to vertical support for the medial gastrocnemius and gluteus maximus in the weakened and full strength models across the gait cycle.

Table 4: Average changes in individual muscle contribution to vertical support between healthy older adults and older adults due to quadriceps weakening

Muscle	Mean Difference (m/s^2)	% Change
Biceps Femoris (lh)	-0.0002	-0.1%
Biceps Femoris (sh)	0.0633	48.1%
Gastrocnemius (Lateral)	-0.0102	-3.1%
Gastrocnemius (Medial)	**0.2188**	**16.5%**
Gluteus Maximus	**0.1799**	**7.4%**
Gluteus Medius	-0.0583	-2.7%
Rectus Femoris	-0.0828	-17.3%
Soleus	-0.9015	-10.7%
Tibialis Anterior	0.0802	3.4%
Vastus Intermedius	-0.1890	-17.6%
Vastus Medialis	-0.3413	-17.8%
Vastus Lateralis	-0.1294	-18.8%

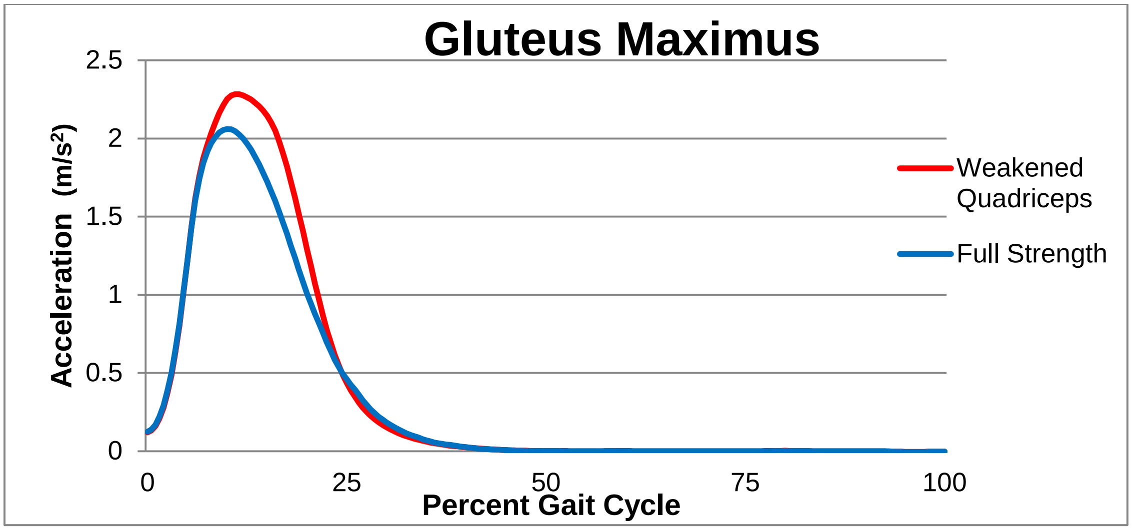

Figure 7: Contribution to vertical support by the gluteus maximus muscle in the weak-ened and full strength model.

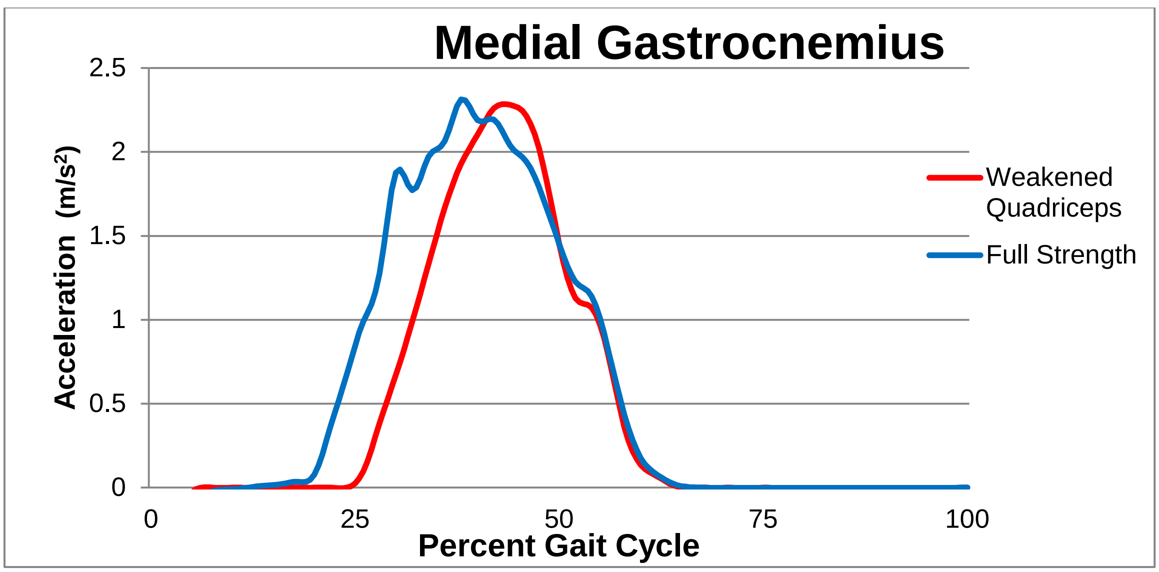

Figure 8: Contribution to vertical support generated by the medial gastrocnemius muscle in the weakened and full strength model

3.3 Contributions to progression in weakened older adults

In order to maintain healthy older adult gait, the gluteus medius and gluteus maximus showed the largest average percent increases in contributions to support and progression for weakened quadriceps (Table 5).The gluteus medius showed the largest percent increase in contributions to propulsion while the gluteus maximus displayed the largest percent increase in contributions to braking. Figures 9 and 10 illustrate the average contributions to progression for the gluteus medius and gluteus maximus in the weakened and full strength models across the gait cycle ($p<0.023$).

Table 5: Average changes in individual muscle contribution to progression between healthy older adults and older adults due to simulated quadriceps weakening

Muscle	Mean Difference (m/s^2)	% Change
Biceps Femoris (lh)	-0.0028	-1.8%
Biceps Femoris (sh)	-0.0134	-7.0%
Gastrocnemius (Lateral)	-0.1101	-48.4%
Gastrocnemius (Medial)	-0.1372	-20.5%
Gluteus Maximus	**-0.0114**	**9.9%**
Gluteus Medius	**0.0085**	**19.1%**
Rectus Femoris	0.1740	-47.5%
Soleus	0.0558	4.5%
Tibialis Anterior	0.0945	-14.1%
Vastus Intermedius	0.0530	-16.3%
Vastus Medialis	0.0956	-16.5%
Vastus Lateralis	0.0370	-17.7%

*Muscles highlighted in red contribute to breaking the body's COM. Muscles highlighted in green contribute to propulsion of the COM.
*A negative % change indicates a decrease in the absolute magnitude of the acceleration

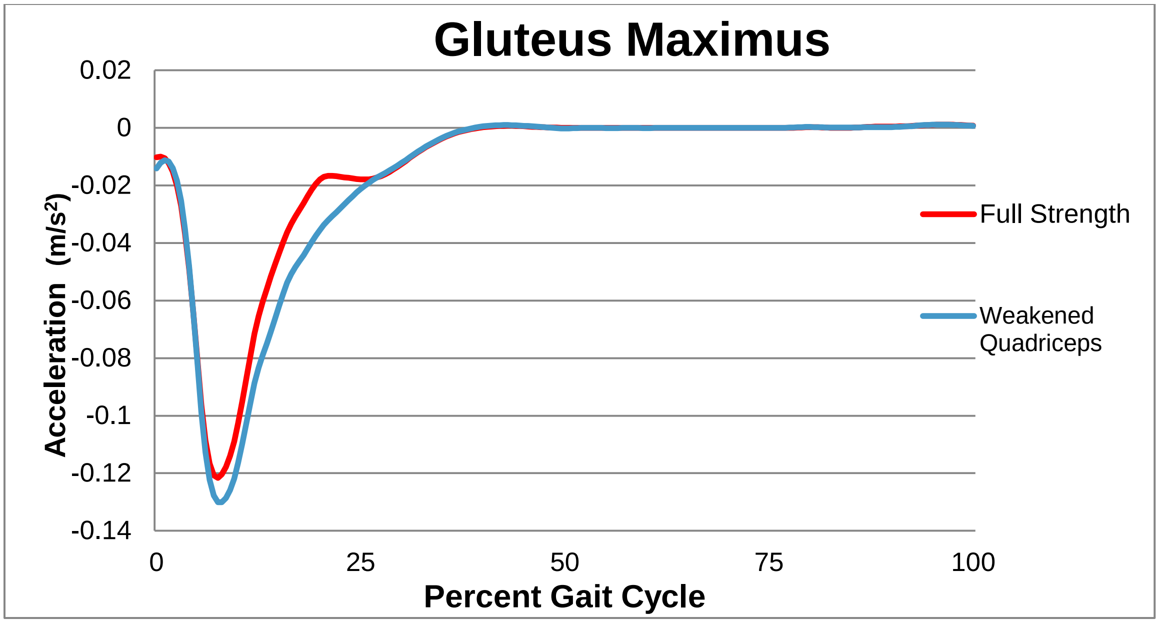

Figure 9: Contribution to progression generated by the gluteus maximus muscle in response to the atrophy and full strength model.

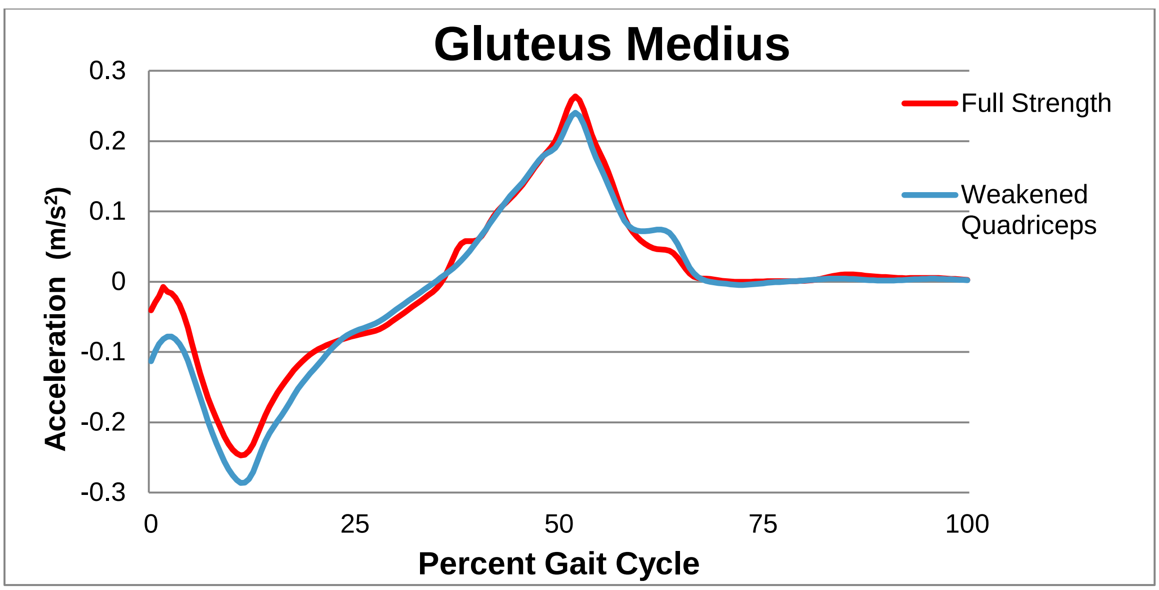

Figure 10: Contribution to progression generated by the gluteus medius muscle in response to the atrophy and full strength model.

3.4 Forces and contributions to support and progression data for older and young adults with weakend quadriceps

Comparisons between which muscles increased their percent changes in muscle force and contributions to support and progression in the weakened older (Table1) and young models (Table A2) from the healthy full strength older (Table A1) and young (Table A3) models, primary muscle compensators were performed. Percent changes in force (Table 6a) and contributions to support (Table 6b) and progression (Table 6c) in response to quadriceps weakness for both young and older weakened adults.

Table 6a: Percent change and average difference of force for older and young adults

Muscle	Older Percent Change from Full Strength	Average Difference (N)	Young Percent Change from Full Strength	Average Difference (N)
Vasti	-27.53%	-59.73	-7.70%	-65.90
Gluteus Maximus	9.00%	45.58	15.90%	62.24
Soleus	-2.90%	-60.53	6.80%	120.95
Biceps Femoris	-9.45%	-23.57	-6.20%	-24.70
Gluteus Medius	-1.00%	-9.46	2.10%	26.76
Tibialis Anterior	-15.40%	-39.43	-3.40%	-18.73
Rectus Femoris	-17.30%	-139.34	-20.70%	-72.20
Gastrocnemius	40.90%	399.71	-10.10%	-97.71

Table6b: Percent change and average difference in contributions to support for older and young adults

Muscle	**Older Percent Change from Full Strength**	**Average Difference (m/s^2)**	**Young Percent Change from Full Strength**	**Average Difference (m/s^2)**

Vasti	-18.1	-0.22	-5.8%	-.25
GluteusMaximus	7.4%	0.17	16.4%	-.33
Soleus	-10.7%	-0.90	6.6%	0.51
Biceps Femoris	24.1%	0.031	-6.1%	-0.03
Gluteus Medius	-2.7%	-0.05	0.9%	0.02
Tibialis Anterior	-3.4%	0.08	-4.3%	-0.24
Rectus Femoris	-17.4%	-0.08	-4.67%	-.025

Table6c: Percent change and average difference in contribution to progression for older and young adults

Muscle	Older Percent Change from Full Strength	Average Difference (m/s^2)	Young Percent Change from Full Strength	Average Difference (m/s^2)
Vasti	-16.8%	0.061	-8.0%	0.14
GluteusMaximus	9.90%	-0.011	20.8%	0.05
Soleus	4.50%	0.055	0.3%	0.01
Biceps Femoris	-4.40%	-0.0081	-6.4%	-0.01
Gluteus Medius	19.10%	0.0085	1.7%	-0.11
Tibialis Anterior	-14.10%	0.094	-3.5%	0.07
Rectus Femoris	-47.50%	0.174	-16.5%	0.11

*Muscles highlighted in red contribute to breaking the body's COM. Muscles highlighted in green contribute to propulsion of the COM.
*A negative % change indicates a decrease in the absolute magnitude of the acceleration

4. DISCUSSION

4.1 Muscle compensations for simulated quadriceps weakness in older adults

Many muscles changed their force output and contributions to support and progression to compensate for quadriceps weakness in older adults. The medial gastrocnemius had the greatest percent change in force output and in its contribution to support from the full strength to the weakened model ($p<0.023$). One of the functions of the gastrocnemius is to provide vertical support during gait. When the quadriceps were weakened a large increase was seen in the medial gastrocnemius and no significant change occurred for the lateral gastrocnemius. The medial gastrocnemius has a larger peak isometric force and higher activation than the lateral gastrocnemius. This could explain the larger increase in force for the medial gastrocnemius, because the more activation and higher peak force a muscle has the higher the ability to contribute to acceleration.

The gluteus medius along with the soleus were found to have the largest percent increase in contribution to propulsion of the body's COM ($p<0.023$). It is important to note that the soleus displayed the largest increase in magnitude for contribution to progression, even though it did not have the highest percent increase. The soleus did not increase its contribution to progression enough to make a large increase in percent change, but it still one of the main muscles contributing to progression during simulated quadriceps weakness. The gluteus medius and soleus can be targeted to be strengthened in order to help older adults maintain normal healthy older adult gait due to their increase in percent change for propulsion and magnitude of force change for propulsion contribution respectively. The gluteus maximus increased its force output and contributions to support and progression from the full strength to the weakened model. As mentioned earlier the function of the quadriceps are to brake the body's COM and provide vertical support during stance. The gluteus maximus increased its peak force and it contributions to braking and vertical support to compensate for the quadriceps weakness.

4.2 Analysis of different individual muscle that compensated for weakened quadriceps in older and young adults

Comparing muscle compensations for quadriceps weakness in young and older adults, it was found that the medial gastrocnemius and soleus were the two muscles that differed the most between age groups. In young adults, the medial gastrocnemius decreased it peak force, while for older adults it increased its peak force. In older adults, the soleus decreased its peak force while the soleus was one of the main muscle compensators in young adults. The lack of increase of force output and contributions to support and progression from the soleus could be a result of its activation maxing out in the models. In both the full strength and atrophy models of the older adults, the soleus maxed out its activation during late stance, which could explain why the soleus did not show an increase in compensations from the full strength to the atrophy model. For both the older and young adults, the gluteus maximus increased its contributions to support. However, in young adults the percent change was higher than in older adults. The soleus decreased its contributions to support in the older adults, and increased its contributions significantly for the young adults. The percent change in muscle contributions to progression was different between older and young adults. This could be a result of the models having different primary compensators, forcing other muscles to increase their contributions to make up for the weakened quadriceps. These differences in percent change may suggest that differences between older adults and younger adult kinematics may affect muscle compensations for quadriceps weakness.

5. CONCLUSION

5.1 Summary

The study estimated muscle forces and contributions to support and progression required to maintain the gait of healthy older adults in response to quadriceps weakness. Major muscles compensators for older adults with weak quadriceps were determined by analyzing percent changes in peak muscle forces and contributions to support and progression in the older adults with weak quadriceps compared to the full strength older adults. The major muscle compensators increasing their peak force were the medial gastrocnemius and gluteus maximus. The medial gastrocnemius displayed the largest percent increase in both its peak force and contribution to support. The gluteus maximus increased in contribution to both support and braking while the gluteus medius and soleus increased their contributions to propulsion of the body's COM. When the older weakened adults were compared to the young weakened adults the gluteus maximus increased its peak force and contributions to support and progression in all cases. The soleus muscle was not found to be as big as of a compensating muscle in older adults as it was in younger adults. The gastrocnemius was found to be more of a primary compensator for older adults than young adults. Differences in the primary muscles compensating for quadriceps weakness may be due to differences in gait between older and young adults. Looking at all three variables, force and contributions to both support and progression, the gluteus maximus was the only muscle to increase its contributions in every area; therefore, strengthening of the gluteus maximus may help compensate for weakened quadriceps in order to maintain normal older adult gait. Along with the gluteus maximus, this study showed that the medial gastrocnemius and soleus were main muscles to target to help older adults maintain normal gait. This finding directly correlates to the results of the previous study, showing that the soleus and gluteus maximus were major compensators for simulated quadriceps [12].

5.2 Limitations

5.2.1 Model Limitations

In the older adult model, the soleus muscle activation maxed out during gait in both the full strength and weakened models. This limited the soleus's ability to compensate for the quadriceps weakness in the older adults. This could explain why the gastrocnemius increased so much in order to compensate for the quadriceps weakness, because the soleus could not produce any more force while maintaining normal older adult walking gait.

5.2.2 Simulation Limitations

The simulations were forced to track normal older adult gait, however, persons with weakened quadriceps, such as individuals with KOA, often do not use normal gait patterns. The findings of this project do offer insight into potential compensation strategies to maintain normal older adult gait. Finally, there was no isometric strength data gathered so the original strength of the subjects' quadriceps was unknown. Without experimental measures of the older adults' quadriceps strength it is unknown what weakness may have already been present in the older adult subjects and how further weakening would affect muscle function during gait.

5.3 Future Work

In the future, using OpenSim and gait simulations to estimate muscle forces and contributions to support and progression, the older adults could be modeled with experimental isometric strength data or MRI data to measure subject specific muscle volumes. Also, one could investigate actual muscle compensation in a confirmed weak quadriceps populations (KOA) compared to healthy older adults.

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Appendix A

TableA1: Peak muscle forces and contributions to support and progression in full strength quadriceps for older adults

Muscle	Average Peak Force (N)	Average Peak Support (m/s^2)	Average Peak Progression (m/s^2)
Biceps Femoris (lh)	251.327738.1901	0.3811	0.1534
Biceps Femoris (sh)	247.5746	0.1315	0.1918
Gastrocnemius (Lateral)	142.70450.1624	0.3284	0.2273
Gastrocnemius (Medial)	976.8721	1.3221	0.6687
Gluteus Maxi-mus	506.1132	2.4154	-0.1157
Gluteus Medius	976.8721	2.1706	0.0445
Rectus Femoris	255.1066	0.479	-0.3664
Soleus	2.05E+03	8.4199	1.2483
Tibialis Anteri-or	256.535	2.3487	-0.6711
Vastus Inter-medius	222.2198	1.074	-0.3259
Vastus Medialis	383.6148	1.9157	-0.5809
Vastus Lateralis	143.5662	0.6886	-0.2088

TableA2: Peak muscle forces and contributions to support and progression in full strength quadriceps for young adults

Muscle	Average Peak Force (N)	Average Peak Progression(m/s^2)	Average Peak Support (m/s^2)
Biceps Femoris (lh)	367.7504714	0.192914286	0.390086
Gastrocnemius (Medial)	1235.2085	1.192628571	5.409271
Gluteus Maximus	403.2407714	-0.247185714	1.853157
Gluteus Medius	1089.641029	-0.528485714	2.205757
Rectus Femoris	760.8064714	-1.578657143	3.834129
Soleus	1741.3	1.593757143	7.324643
Tibialis Anterior	566.9725714	-1.802557143	6.720186
Vasti	283.5257143	-0.525342857	0.468043

TableA3: Peak muscle forces and contributions to support and progression in weakened quadriceps for young adults

Muscle	Average Peak Force (N)	Average Peak Progression(m/s^2)	Average Peak Support (m/s^2)
Biceps Femoris (lh)	343.0644286	0.178757143	0.357029
Gastrocnemius (Medial)	1137.5444	1.086757143	5.075043
Gluteus Maximus	464.3998429	-0.294771429	2.127
Gluteus Medius	1116.314229	-0.537357143	2.221429
Rectus Femoris	694.9230714	-1.438714286	3.585343
Soleus	1862.171429	1.602585714	7.834114
Tibialis Anterior	548.3355	-1.735657143	6.476457
Vasti	266.2755429	-0.485571429	0.453214